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Observational Case Studies and Diagnostic Analyses of Long-Lived Large-Amplitude Inertia-Gravity Waves

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13. ABSTRACT *(Maximum 200 words)*

AFOSR-funded research projects have included: (1) completion of a national climatology of large-amplitude inertia-gravity wave (IGW) occurrences, (2) completion of a case study from 15-17 November 1987 of a long-lived convective event that featured a complex interplay between wake-low troughs and IGWs, (3) completion of a case study of the 4 January 1994 large-amplitude IGW event over the northeastern United States, and (4) ongoing research designed to elicit the environmental structure (horizontal and vertical) of large-amplitude IGWs. The results from (1) reveal that IGWs are favored in interior regions east of the Rockies while avoiding the mountainous western United States. The analysis from (2) shows that rain-cooled air provides the necessary low-level wave duct for IGWs and wake-low troughs to coexist in an organized convective environment. The results from (3) suggest that vigorous subsynoptic-scale ascent can play the role of surrogate convection in allowing IGW organization and amplification provided that the ascent has roots in a prominent low-level wave duct. Preliminary results from (4) reveal that the environment of large-amplitude IGWs is remarkably similar to warm front environments except that the upper-level jet is stronger and the low-level thermal inversion is better defined in the IGW cases.

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Structure of large-amplitude propagating gravity waves

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Observational Case Studies and Diagnostic Analyses of Long-Lived Large-Amplitude Inertia-Gravity Waves

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17 December 1996

I. SUMMARY OF RESEARCH PROGRESS

1) Completed Work:

a) Lorna Koppel completed her Master's thesis in December 1995. The cover page of her thesis and the abstract are attached to this report.

b) W. Edward Bracken completed his Master's thesis in October 1995. The cover page of his thesis and abstract are attached to this report.

c) A draft manuscript has been prepared summarizing the principal findings of our analysis of the large-amplitude inertia-gravity wave (IGW) event of 4 January 1994 over the northeastern United States. This manuscript is being submitted to the *Monthly Weather Review* for formal publication in December 1996. A copy of the title page and the abstract is included.

2) Ongoing Work:

a) Eric Hoffman has used the dates of IGWs identified by Koppel (1995) to construct composite analyses of IGW environments using the National Climate Data Center (NCDC) sounding data for 1946-1992 stored on CD-ROM and gridded European Centre for Medium-Range Weather Forecasts (ECMWF) analyses obtained from the National Center for Atmospheric Research (NCAR). Recent preprints from the 15th American Meteorological Society Conference on Weather Analysis and Forecasting, 19-23 August 1996, Norfolk, VA, and the 7th American Meteorological Society Conference on Mesoscale Processes, co-sponsored by the Royal Meteorological Society, 9-13 September 1996, Reading, United Kingdom, are attached.

b) It is expected that the salient results of the Koppel (1995) IGW climatology and the Bracken (1995) IGW and wake trough case study will be written up and submitted for formal publication in FY-97. As of December 1996 work is preceding on the preparation of the Koppel (1995) thesis results for formal publication. It is anticipated that a manuscript will be submitted to the *Monthly Weather Review* describing the salient features of her results by March or April 1997. Once this paper is completed work will begin on preparing the key findings from Bracken (1995) for formal publication. This submission is expected to be made to the *Monthly Weather Review.*

Task I.1a established the first comprehensive IGW national climatology. The critical finding was that IGW occurrence is maximized along a north-south oriented band across the Plains. Secondary maxima are found across much of the Great Lakes region and interior northeastern United States. IGWs are absent over the mountainous western United States, indicative of the importance of low-level stable layers (wave ducts) to the propagation of large-amplitude IGWs. Such stable layers are rare in the mountainous western United States, given the near-absence of warm frontal inversions in this region.

Task I.1b demonstrated that surface weather variations associated with the passage of large-amplitude IGWs and large-amplitude wake-low troughs behind active convective regions could be virtually indistinguishable. In this case the low-level wave duct was provided by widespread rain-cooled air. Wake-low troughs, triggered by descending air near the back edge of the convective line, tended to remain colocated with the rear of the stratiform rain region, whereas IGWs, likely triggered in association with the passage of prominent jet streaks aloft, tended to propagate through the convective region in the direction of the low-level frontal inversion downstream.

Task I.1c revealed the three-dimensional structure of a large-amplitude IGW over the northeastern United States on the basis of data obtained from fortuitously situated National Weather Service 88D Doppler radars and wind Profiler sites. Vigorous deep ascent between a

strong upstream trough and a prominent downstream ridge appeared to play an important role in triggering IGW intensification. This strong ascent extended downward into an unusually strong low-level wave duct and was accompanied by large parcel accelerations in the upper troposphere as the separation distance between the aforementioned trough and ridge collapsed to almost 500 km.

Ongoing research on Task I.2a has shown that large-amplitude IGWs exist in an environment characterized by warm air advection (veering winds, low-level frontal inversion, jet aloft) on the basis of sounding composites gleaned from radiosonde data taken from the NCDC CD-ROM. The composite soundings compared favorably to typical warm front soundings with the exception that the frontal inversion (wave duct) and vertical wind shear and associated jet structure were noticeably stronger in the IGW composites. Composite isobaric analyses of large-amplitude IGW events disclosed that the waves tended to cluster beneath prominent southwesterly flow aloft associated with a propagating jet streak/trough/ridge system.

Ongoing Task I.2b will be accomplished with the preparation of formal manuscripts for submission to the refereed literature.

II. CURRENT PROJECT STATUS:

Aside from submission of our results for formal publication we have completed the tasks as modified from our original proposal. Current work is focused on Eric Hoffman's doctoral dissertation research using funds provided by the 1995 ASSERT supplement.

III. PUBLICATIONS:

(a) refereed:

i. Completed: none

ii. Submitted December 1996:

Bosart, L. F., A. Seimon, W. E. Bracken, and W. R. Snyder, 1996: The extreme large-amplitude inertia-gravity wave event of 4 January 1994 over the northeastern United States. *Mon. Wea. Rev.*, **125**, (submitted).

(b) preprints:

Hoffman, E. G., L. F. Bosart, and D. Keyser, 1996: Large-amplitude inertia-gravity wave environments: Vertical structure and evolution. Preprints, 15th Conference on Weather Analysis and Forecasting, American Meteorological Society, 19-23 August 1996, Norfolk, VA, pp. 245-248.

Hoffman, E. G., L. F. Bosart, and D. Keyser, 1996: Large-amplitude inertia-gravity wave environments: Vertical structure and evolution. Preprints, 7th American Meteorological Society Conference on Mesoscale Processes, co-sponsored by the Royal Meteorological Society, 9-13 September 1996, Reading, United Kingdom, pp. 562-564.

IV. PROJECT PERSONNEL:

Co-PIs:	Lance F. Bosart
	Daniel Keyser
Staff Support:	Anton Seimon
Graduate Students:	Lorna Koppel (September 1993 - December 1995)
	W. Edward Bracken (beginning October 1993)
Administrative Support:	Celeste Iovinella

V. BUDGET:

Support consists of 1995 ASSERT supplement to fund Eric Hoffman's doctoral dissertation research.

VI. TECHNOLOGY TRANSITIONS:

Dr. John Zack, President, Meso, Inc., 185 Jordan Road, Troy, New York 12180, has run his mesoscale model (MASS) on the large-amplitude IGW event of 4 January 1994 in response to the presentation of preliminary research results from this case by Co-PI Bosart at the July 1994 6th Conference on Mesoscale Processes, sponsored by the American Meteorological Society, in Portland, Oregon. Dr. Zack is interested in understanding and predicting the details of complex weather situations. He and Dr. Michael Kaplan of Newport News, VA, plan to conduct future simulations of this event using an improved version of the MASS model. Dr. Zack has a complete set of our analyses for this case.

Dr. Ying-Hwa Kuo and Dr. Jordan Powers of the Mesoscale and Microscale Meteorology (MMM) division of NCAR (P.O. Box 3000, Boulder, CO 80307) are interested in possibly simulating the large-amplitude IGW event of 4 January 1994 using the NCAR/Penn State MM5 model. They have obtained our detailed analyses for this case. Dr. Powers (with Dr. Richard J. Reed) has conducted the first known successful simulation of a large-amplitude IGW for the 15 December 1987 case over the midwestern United States.

Forecasters at the Raleigh, North Carolina, Albany, New York, and Taunton, Massachusetts, offices of the NWS have spoken with Bosart over the last year (most recently at the 15th American Meteorological Society Conference on Weather Analysis and Forecasting, 19-23 August 1996, Norfolk, Virginia) about how to apply our IGW research findings to NWS operations. Co-PI Bosart has been invited to present a seminar at North Carolina State University on this and related subjects during the 1996-1997 academic year.

7. INVENTIONS AND PATENTS:

None.

8. HONORS/AWARDS:

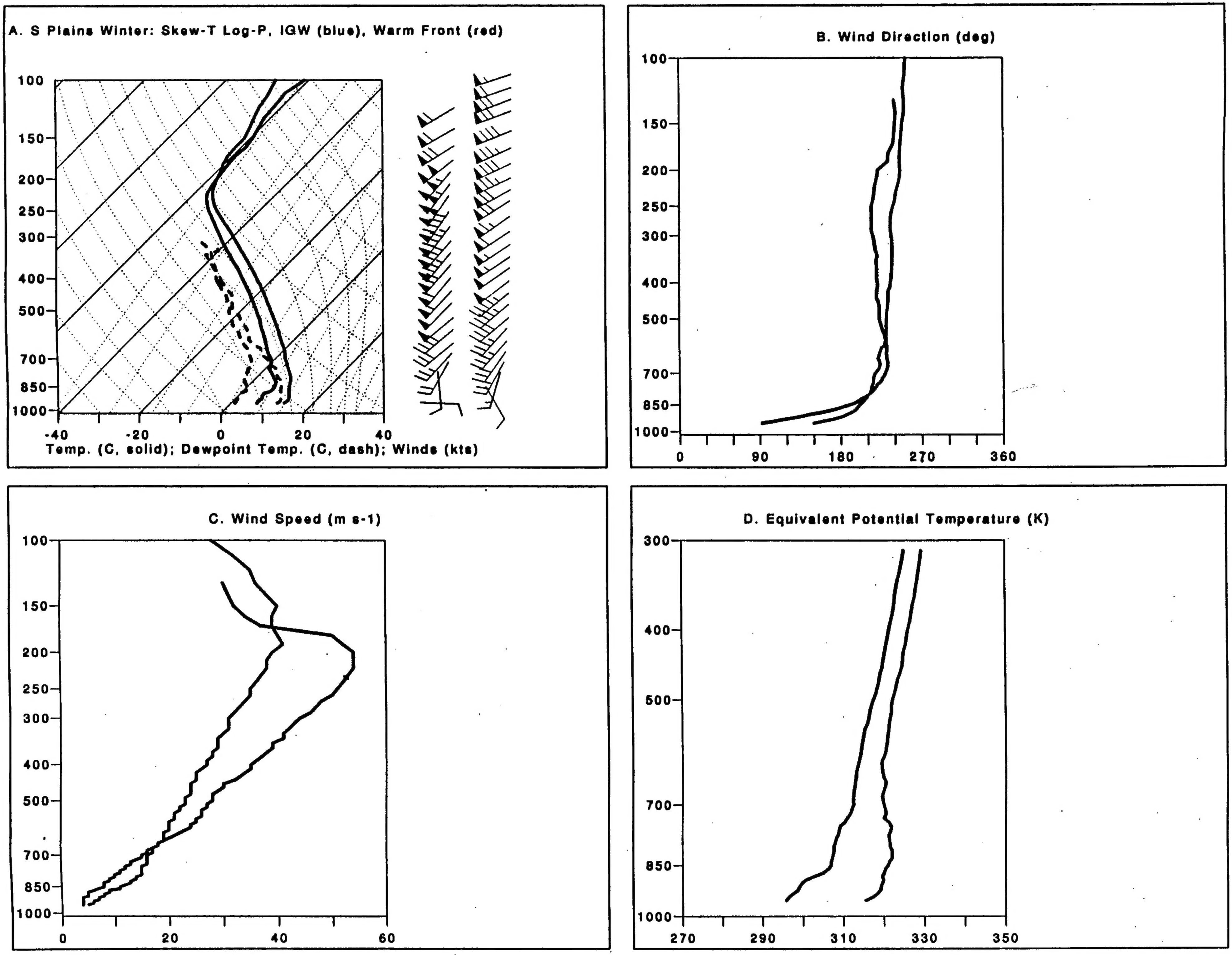
None during the grant period. However, the Co-PIs have been recognized for their significant research and professional service contributions by the American Meteorological Society (AMS) as follows:

Lance F. Bosart	Daniel Keyser
Elected AMS Fellow: 1983	Clarence L. Meisinger Award: 1989
Jule G. Charney Award: 1992	Editor's Award (AMS *Mon. Wea. Rev.*): 1989

(a) Fig. 1:

Composite (8 events) Southern Plains winter large-amplitude IGW soundings (blue) of: (a) temperature, dew point temperature and winds, (b) wind direction, (c) wind speed, and (d) equivalent potential temperature. Units are C for temperatures, K for equivalent potential temperature, and knots for the winds in conventional format. For comparison we show in red similar soundings for composite (32 events) winter warm fronts.

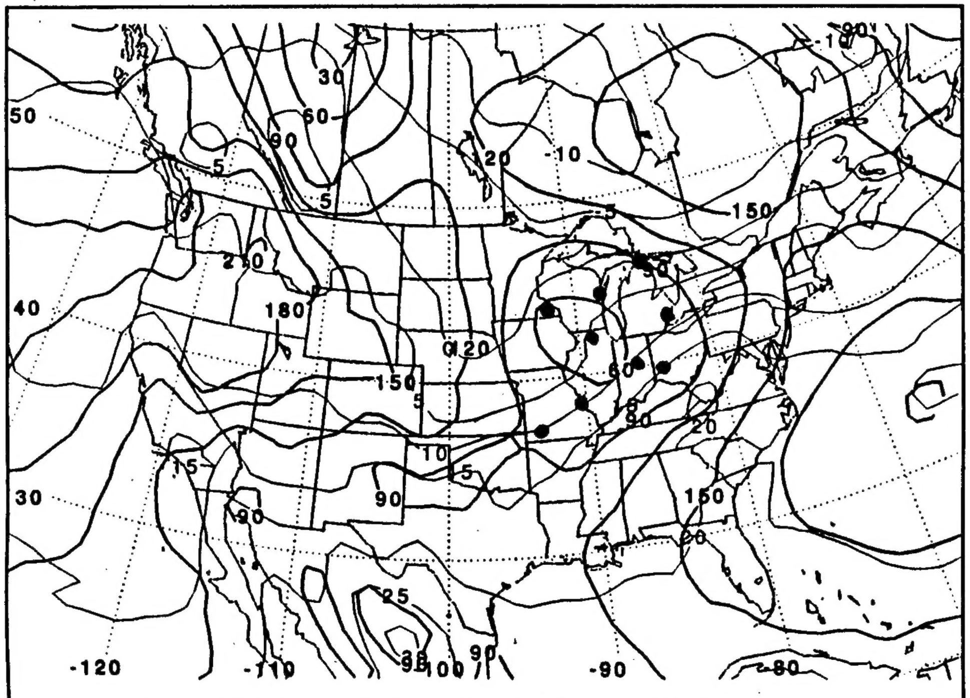
Figure illustrates that IGWs are accompanied by stronger wind shear and a more pronounced jet just below 200 hPa (c), veering winds, a colder troposphere and a stronger stable layer (a), a more meridional flow in the middle and upper troposphere ahead of a likely stronger upstream trough (b) and a more stable atmosphere overall (d).


A. S Plains Winter: Skew-T Log-P, IGW (blue), Warm Front (red)
100
150
200
250
300
400
500
700
850
1000
-40
-20
0
20
40
Temp. (C, solid); Dewpoint Temp. (C, dash); Winds (kts)
B. Wind Direction (deg)
0
90
180
270
360
C. Wind Speed (m s-1)
0
20
40
60
D. Equivalent Potential Temperature (K)
270
290
310
330
350

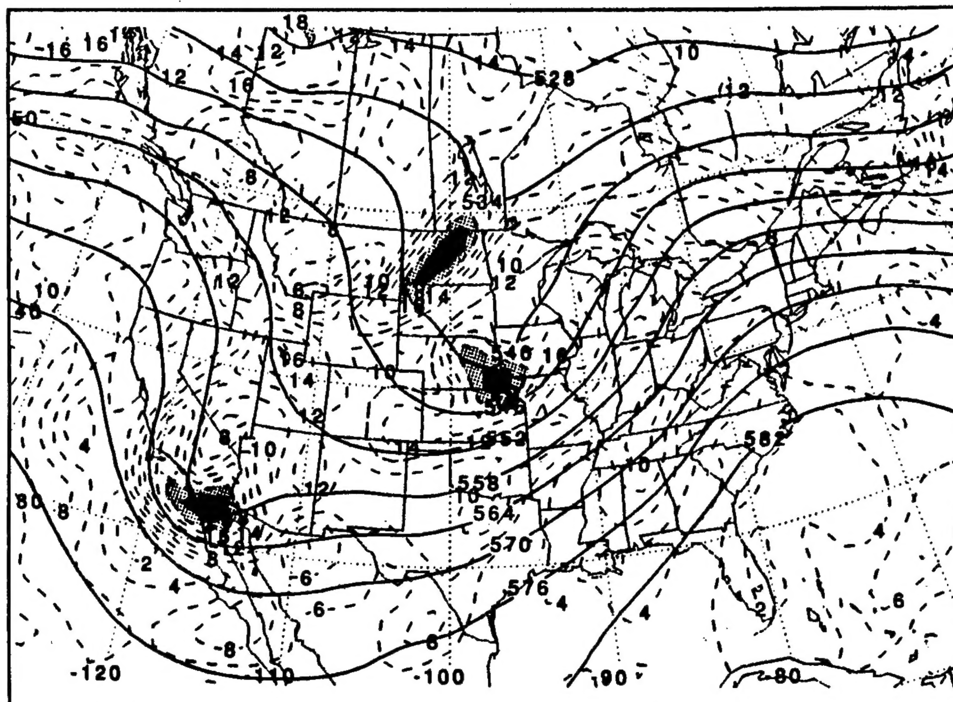
(b) Fig. 2:

Composite (8 events) flow maps for Midwest winter large-amplitude IGWs: (a) 1000 hPa heights (blue, every 30 m) and temperatures (green, every 5°C), (b) 500 hPa heights (blue, every 6 dam) and absolute vorticity (dashed, every 2×10^{-5} s^{-1}), (c) 300 hPa heights (blue, every 12 dam) and winds (dashed, 10 knots and then every 20 knots and colored above 70 knots), and (d) a dynamical tropopause map based on the 1.5 potential vorticity unit (1.0 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}) surface; winds (green) in knots and pressure (blue, every 50 hPa and colored above 300 hPa). Solid dots in (a) show the position of the IGW events taken from Koppel (1995).

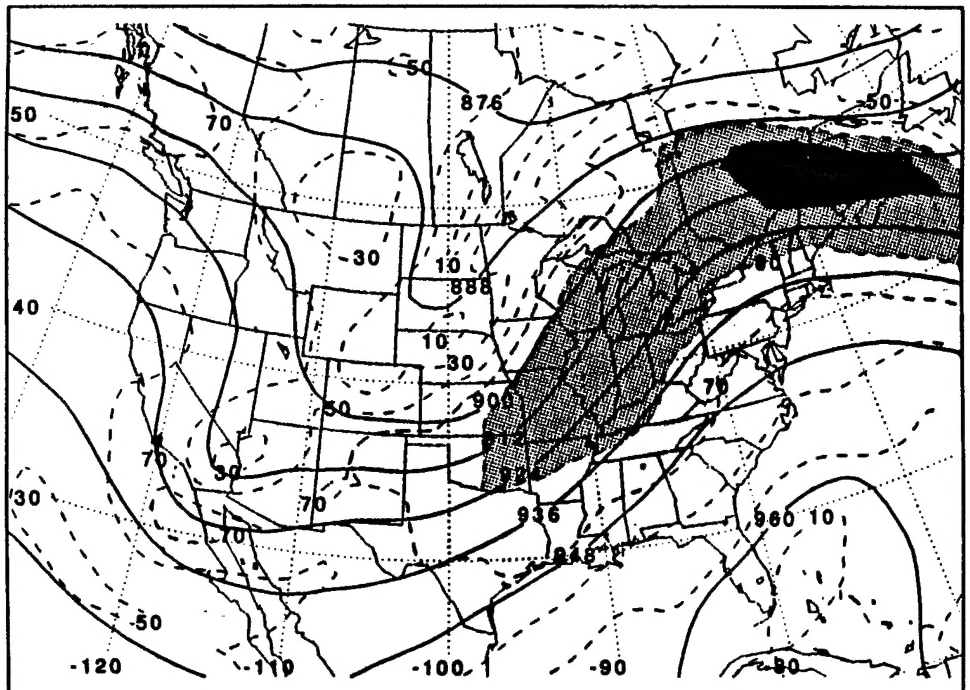
Figure illustrates that IGWs occur near and downstream of the cyclone center and poleward of the warm air (a), in advance of a prominent 500 hPa short wave and vorticity center (b), near the inflection point of the 300 hPa flow upstream of a jet streak and slightly downstream of a second and weaker jet streak (not resolved by the contour interval) (c), and downstream of a locally depressed dynamic tropopause marking a strong short-wave trough (d).



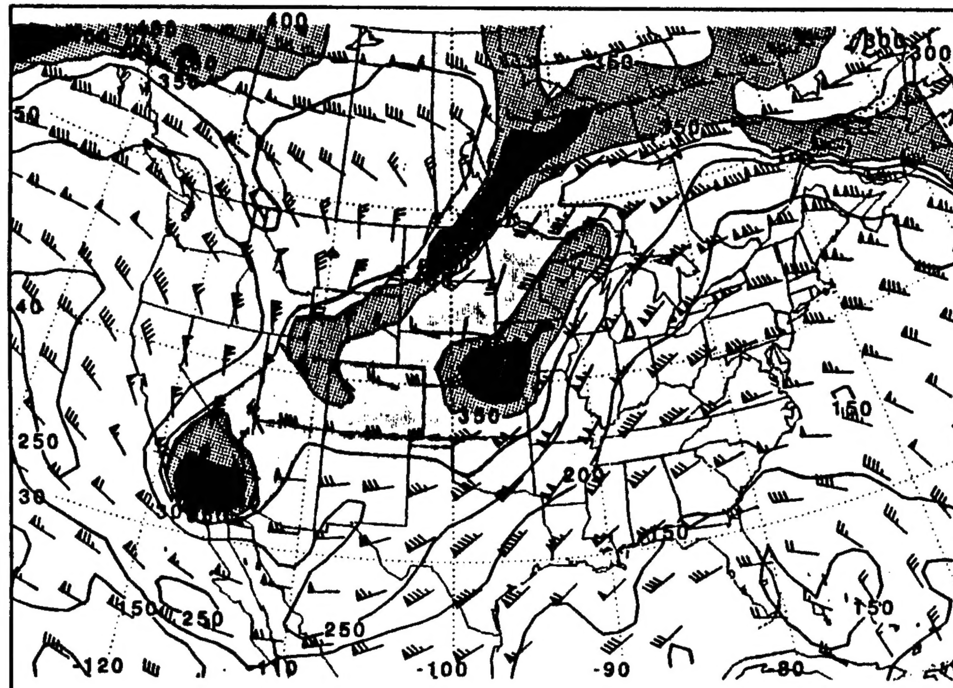
A. Midwest Winter: 1000hPa Height (blue, m, int=30), Temperature (green, C, interval=5)



B. Midwest Winter: 500hPa Height (blue, x10-1 m, int=6), Abs. Vorticity (dashed, x10-5 s-1, shaded > 16)



C. Midwest Winter: 300hPa Height (blue, x10-1 m, int=12), Isotachs (dashed, kts, int=20, shaded > 70)



D. Midwest Winter: Pressure (hPa, int=50, shaded > 300) on Dynamic Trop. (1.5 PVU, above), Winds (kts)

Climatology of
Large-Amplitude Inertia-Gravity Waves
in the Conterminous United States

Abstract of
a thesis presented to the Faculty of
the University at Albany, State University of New York
in partial fulfillment of the requirements
for the degree of

Master of Science
College of Arts and Sciences
Department of Atmospheric Science

Lorna L. Koppel
1995

Abstract

This study examines 25 years of hourly observations for the conterminous United States in order to identify all occurrences of large-amplitude inertia-gravity waves (IGW) with hourly surface pressure changes of at least + 4.25 hPa. The data period covers 1949 through 1963 and 1984 through 1993. Geographic, seasonal, and diurnal variations of IGW activity are examined, along with weather perturbations associated with wave passage. Synoptic signatures associated with IGWs also are studied through use of composited mean sea level pressure and 500 hPa geopotential height fields for approximately half of the IGW events.

This study found 579 large-amplitude IGW events affecting 1038 stations. An average of 23 events per year was noted for the conterminous US. Almost all (97%) of the IGWs were waves of depression. Most (80%) of the surface pressure perturbations were between -4.25 hPa and -6.25 hPa. The maximum pressure perturbation was - 13.0 hPa h^{-1}. The following weather-related perturbations were also found with wave passage: backing winds with a vector shift from 112° at ~ m s^{-1}; precipitation ending with or just after wave passage; ceiling heights and visibility increasing; and temperature (dewpoint) increasing (decreasing).

The occurrence of IGWs is restricted to primarily east of the Rockies in general and along three axes in particular: (1) one maximum is situated along a northwest-southeast curved axis from South Dakota through Minnesota, southern Wisconsin, northern Illinois, and western Michigan; (2) a second maximum lies along a north-south axis from southern Iowa, eastern Kansas, and western Missouri; and (3) a third maximum runs along an east-west axis through Oklahoma, Arkansas, northern Mississippi, and northern Alabama.

The maxima (minima) in IGW occurrences is at 0300 and 1100-1300 LST (0500 0700 and 1600-2100 LST). The early morning maximum appears to be heavily influenced by convection in the Central US in the late spring and early summer. IGWs occur predominantly in the spring with a secondary maximum in the late fall through winter. There is a definite decrease in IGW

activity in the late summer through early fall. IGWs also have an intraannual variation in locations where they occur. The basic cycle begins in the Northeast in January and shifts in a clockwise manner though the eastern half of the US for the rest of the year.

Composite synoptic patterns for 295 IGW events were grouped into 16 cases, and seasonal variations in these synoptic patterns were noted. The synoptic signatures associated with 69% (11 of the 16) of the cases match the conceptual model of Uccellini and Koch (1987, hereafter U&K87) and occurred in November through April. The following features were noted: (1) the areas of IGW activity were confined between the southwesterly flow inflection axis and the downstream ridge axis in the 500 hPa height field; (2) all had strong warm air advection; (3) most cases had a sea level low pressure center to the southwest of the area of IGW activity; and (4) the regions of IGW activity were usually under or near the cyclonic exit region of a southwesterly jet streak at 500 hPa. An additional 13% of the cases (2 of 16) occurred in May and June, displayed the synoptic signature of U&K87, and had coupled 500 hPa jet streaks similar to the work of Uccellini and Kocin (1987). However, 19% of the cases studied (3 of 16) occurred in July and August and did not conform to the U&K87 model. In these cases the areas of IGW activity were under northwesterly flow aloft and between the 500 hPa height ridge and downstream inflection axes. These cases are similar to the work by Johns (1982, 1984).

The Severe Weather Outbreak of

15-17 November 1987:

A Multiscale Case Study

Abstract of

a thesis presented to the Faculty

of the University at Albany, State University of New York

in partial fulfillment of the requirements

for the degree of

Master of Science

College of Arts and Sciences

Department of Atmospheric Science

W. Edward Bracken
October 1995

ABSTRACT

A multiscale case study of a severe weather outbreak in the Lower Mississippi River Valley on 15-17 November 1987 is presented. Data used includes European Centre for Medium Range Forecasting model output and surface and upper-air observations. Results show the important interaction between many different scales of motion during the evolution of the event. Planetary-scale low frequency disturbances with horizontal and temporal scales on the order of 10^3 km and 7-10 d respectively, are observed to amplify just prior to the onset of the event. The result is a quasi-stationary, upper-tropospheric trough-ridge couplet over the southwestern United States which acts to increase the subtropical jet over northern Mexico and southern Texas. A series of transient eddies, or synoptic-scale disturbances, embedded within the larger scale flow move into the planetary-scale trough and amplify as they near the base of the trough. Potential vorticity (PV) and PV-thinking concepts are used to elucidate the structure and behavior of the transients.

The movement of upper-tropospheric PV anomalies over a highly unstable low-level airmass over the southcentral US is observed to be closely associated with the initiation and possible sustainment of two large mesoscale convective systems (MCS). To the rear of these MCSs a total of nine mesoscale wave disturbances (MWD) are identified. Four MWD are identified as wake lows/troughs and five are identified as inertia-gravity waves. Throughout their life-cycles the wake lows/troughs are observed to propagate eastward at 10-15 m s^{-1}. The wake lows/troughs remain affixed to the western edge of the MCS precipitation shield and are accompanied by pressure falls of 5-7 hPa h^{-1}. The wake lows/troughs typically last 5-25 h with one wake low in particular lasting at least 36 h. In contrast, the inertia-gravity waves are not consistently observed to be coincident with the western edge of the MCS precipitation shield, propagating both northeast and northwest at 25-30 m s^{-1}. The inertia-gravity waves are long-lived (~5-18 h) and accompanied by pressure falls as high as 10 hPa h^{-1}. Results suggest that convection, geostrophic adjustment, and shearing instability process may all be possible inertia-gravity wave genesis mechanisms.

A Study of Cyclone Mesoscale Structure with Emphasis on a Large-Amplitude Inertia-Gravity Wave

by

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December 1996

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Abstract

An analysis is presented of prominent mesoscale structure in a moderately intense cyclone with emphasis on a long-lived, large-amplitude inertia-gravity wave (IGW) that moved through the northeastern United States on 4 January 1994. As the IGW amplified (peak crest-to-trough pressure falls exceeded 13 hPa $(30\ \mathrm{min})^{-1}$), it also accelerated away from the cyclone, reaching a peak forward speed of 35-40 m s^{-1} across eastern New England. The IGW was one of three prominent mesoscale features associated with the cyclone, the others being a weak offshore precursor warm-frontal wave and an onshore band of heavy snow ("snow bomb") in which peak hourly snowfalls of 10-15 cm were observed. None of these three prominent mesoscale features were well forecast by existing operational prediction models, particularly with regard to precipitation amount, onset and duration. The observed precipitation discrepancies illustrate the subtle but important effects of subsynoptic-scale disturbances embedded within the larger scale cyclonic circulation. The precursor offshore warm-frontal wave was instrumental in reinforcing the wave duct preceding the IGW. The "snow bomb" was one indication of the vigor of the ascent and associated large divergence (convergence) in the upper (lower) troposphere and resulting parcel accelerations in the IGW environment.

Small-amplitude IGWs (<1 hPa) are first detected over the southeastern United States from surface microbarogram records and are confirmed independently by the presence of organized and persistent mesoscale cloud bands oriented approximately along the wave fronts. The area of IGW genesis is situated poleward of a weak surface frontal boundary where there is a weak wave duct (stable layer) present in the lower troposphere. In the upper troposphere the region of IGW genesis is situated on the forward side of a deep trough where there is significant cyclonic vorticity advection by the thermal wind. We hypothesize that shearing instability plays a prominent role in IGW genesis, given that the Richardson number is less than unity and a critical level is present throughout much of the middle troposphere in the region of IGW origin. Weak and generally decaying convective activity is also noted in a portion of the IGW genesis region.

The large-amplitude IGW originates on the downstream edge of the northeastward-advancing packet of small-amplitude IGWs. Wave amplification occurs near the upstream edge of a high, cold cloud shield that generally marks the warm conveyor belt. Although it is not possible to conclusively state whether the amplifying IGW forms in situ or grows from a predecessor disturbance, rapid amplification occurs: (1) as the advancing wave encounters an increasingly deeper and stronger wave duct, possibly permitting wave overreflection, in the cold air damming region east of the Appalachians, and (2) downstream of an especially prominent 500 hPa absolute vorticity maximum ($>42 \times 10^{-5}$ s^{-1}). The IGW amplification region is also characterized by: (1) increasingly vigorous and deep subsynoptic-scale ascent associated with the decrease of the distance between the midtropospheric trough and the downstream ridge to < 600 km, (2) upper-tropospheric divergence values ~$5\text{-}10 \times 10^{-5}$ s^{-1}, and (3) an area in the upper troposphere where the ratio of divergence to absolute vorticity is > unity. Available National Weather Service 88D Doppler radar and wind profiler observations are employed to illustrate the rich, time dependent, three dimensional structure of the IGW. Finally, our results suggest that large parcel accelerations are likely and that geostrophic adjustment processes are probably important to the observed IGW amplification.

Preprints, 15th Conference on Weather Analysis and Forecasting.
Norfolk, VA, Amer. Met. Soc., August 1996.

8.5 LARGE-AMPLITUDE INERTIA-GRAVITY WAVE ENVIRONMENTS: VERTICAL STRUCTURE AND EVOLUTION

Eric G. Hoffman*, Lance F. Bosart and Daniel Keyser

University at Albany
State University of New York
Albany, New York

1. INTRODUCTION

Many previous observational studies of inertia-gravity waves (IGWs) have focused on identifying and describing the wave behavior and structure (e.g., Bosart and Seimon 1988; Koch and Golus 1988; Schneider 1990; Seimon et al. 1995). Recently, other studies have begun to investigate the synoptic-scale environments in which IGWs evolve. For example, Uccellini and Koch (1987) showed that for a small sample (13) of published case studies, IGWs occur primarily poleward of a surface frontal boundary beneath the inflection point between an upstream trough and downstream ridge. Uccellini and Koch (1987) also observe a jet streak moving through the trough into the downstream ridge and suggest that geostrophic adjustment may be an important IGW initiation mechanism. A more extensive climatology of large-amplitude IGW events (defined on the basis of hourly surface pressure changes > 4.5 hPa) has recently been compiled by Koppel (1995). This is the first climatology that identifies the spatial, seasonal and diurnal distribution of IGWs in the United States

In general, the vertical structure and evolution of the IGW environment has proved difficult to document because of inadequate temporal and spatial data resolution. However, the vertical structure of individual IGW events has been described in detail, utilizing special ancillary observations, by Ralph et al. (1993) and Ramamurthy et al. (1993). They find low-level inversions capable of acting as wave ducts superposed by a near-neutral layer containing a wave critical level. These vertical structures match well with the theoretical model proposed by Lindzen and Tung (1976) for IGW maintenance. Although these IGW studies have documented the existence of wave ducts and wave critical levels, the characteristic vertical structure of the IGW environment and its evolution have yet to be fully elucidated.

Knowledge of the relationship between the synoptic-scale environment and the life cycle and evolution of IGWs is critical to an increased understanding of wave genesis mechanisms, an important unresolved scientific issue, and to making short-term forecasts of the significant weather events often associated with wave passage. Therefore, the goal of this research is to identify the evolution and characteristic vertical structures of environments conducive to the formation and presence of large-amplitude IGWs. The vertical structure of IGW environments is examined by constructing seasonal and regional composites of soundings nearest to the IGW occurrences identified by Koppel (1995). Since our research is tied closely to Koppel (1995), a brief review of her methodology and results is presented in section 2. Section 3 will describe the data and the objective sounding composite methodology. A discussion of our results is presented in section 4.

2. IGW CLIMATOLOGY

Koppel (1995) identified large-amplitude IGW occurrences (hereafter, IGW will refer to large-amplitude IGWs) in the United States through subjective examination of hourly station pressure changes greater than 4.5 hPa from a network of 150–200 National Weather Service observing stations. The hourly surface reports were available from archives at the National Center for Atmospheric Research (NCAR) for two periods: 1949–1963 and 1984–1993. She further subjectively partitioned IGW occurrences into two categories: 1) IGWs associated with other meteorological events (i.e., convection or cyclone passage) and 2) distinct IGWs. Koppel (1995) then constructed maps of the regional, seasonal, and diurnal distribution and frequency of IGWs, an example of which appears in Fig. 1.

Her primary results indicate that IGWs occur almost exclusively east of the Rocky Mountains (see Fig. 1). The maximum IGW frequency occurs along a generally north-south axis extending from the upper Midwest into Arkansas and Oklahoma. Secondary axes extend eastward from the primary axis across the Great Lakes and the Southeast. IGW activity is virtually absent over the mountainous western United States and is uncommon over portions of the central Appalachians and Florida. This pattern is consistent with the relatively infrequent occurrence of low-level stable layers (wave ducts) associated with warm fronts in these regions.

The monthly frequency distribution (not shown) indicates a maximum in the late winter/early spring

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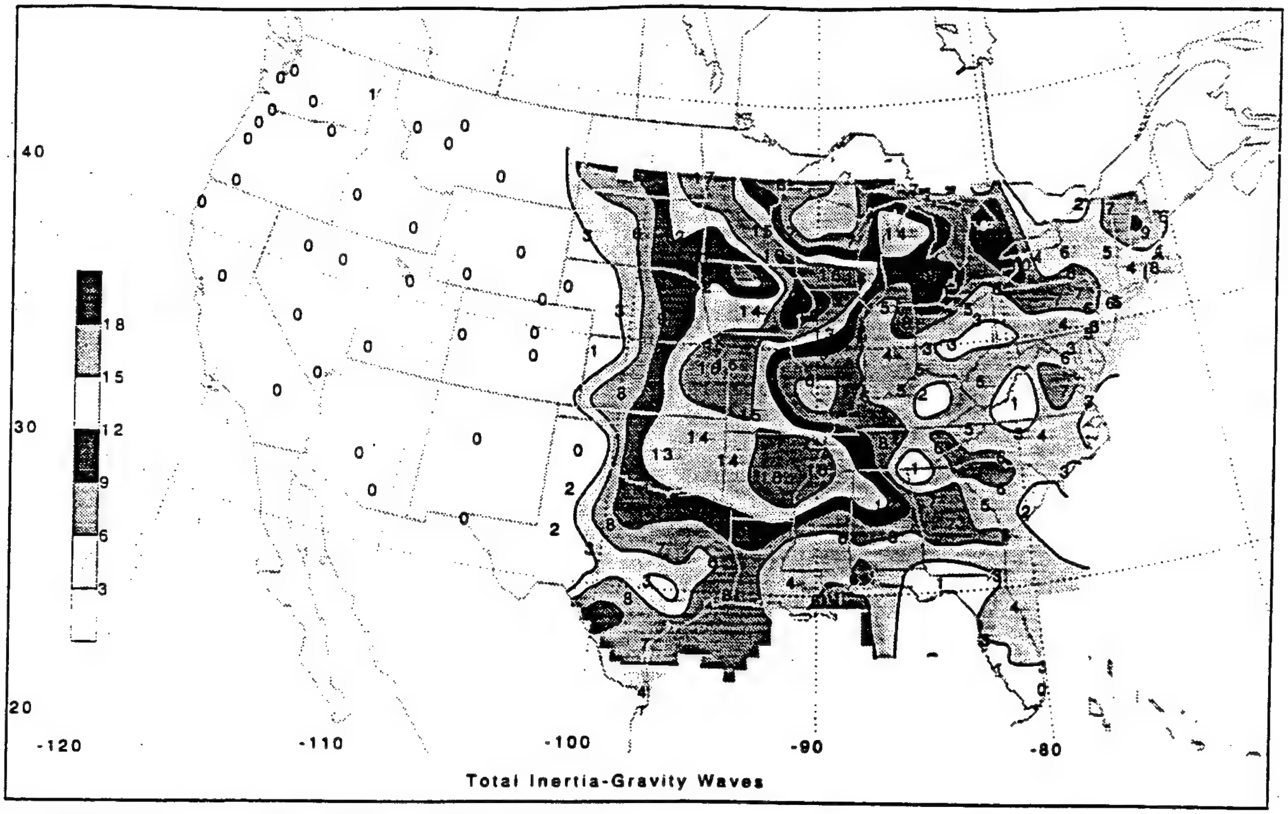

Figure 1. 25-year (1949–1963 and 1984–1993) inertia-gravity wave climatology. After Koppel (1995).

(Feb., Mar., Apr.) and a minimum in late summer/early fall (Aug., Sept., Oct.). The diurnal distribution (not shown) shows two peaks: one near 0300 LST and a second, higher maximum near 1200 LST. Koppel (1995) also showed composite 500 hPa and surface structures for IGW events that correspond closely to the synoptic signatures outlined by Uccellini and Koch (1987).

3. IGW SOUNDING COMPOSITES

3.1 Data and Methodology

Construction of regional and seasonal composite soundings associated with IGWs is accomplished using Koppel's (1995) results and the North America sounding data (1946–1992) archived on compact disc (CD). An objective methodology has been used to identify the individual soundings of the composite. Our composite is restricted to soundings corresponding only to those IGW events that Koppel (1995) categorized as distinct (see section 2). The three closest sounding stations in time and in space to each IGW occurrence are identified excluding those soundings stations located far to the southeast of the IGW (see Fig. 2). Exclusion of soundings in this sector is based on results from Uccellini and Koch (1987) and Koppel (1995) indicating that IGWs occur primarily poleward of warm fronts. Soundings in the excluded area are more likely to be located in the warm sector of a cyclone, equatorward of the warm front. We search the sounding CD data and include the closest sounding of the three for which data are available. Individual soundings corresponding to multiple IGW occurrences are only added to the composite once. After the appropriate sounding has been identified, the temperature, dewpoint, height, and u and v wind components are linearly interpolated with respect to the log of pressure to 10 hPa increments from 1000 to 100 hPa. Finally, because climatological temperatures in the troposphere vary seasonally and spatially, each sounding is identified with one of four regions (see Fig. 3): 1) Midwest, 2) Northeast, 3) Southern Plains and 4) Southeast. Each variable is composited by season and region at the interpolated levels.

3.2 *Results*

For the 347 occurrences of distinct IGWs ('49–'63 and '84–'93) identified by Koppel (1995), a total of 299 soundings are available for the composite. Several features common to the composite soundings in all regions for the winter and spring can be seen in the winter Midwest (Fig. 4a) and spring Northeast (Fig. 4b) composites. Most prominently, a low-level inversion extends from the surface to at least 850 hPa (Fig. 4b) and sometimes to above 700 hPa (Fig 4a). The winds in this inversion veer from easterly or southeasterly to

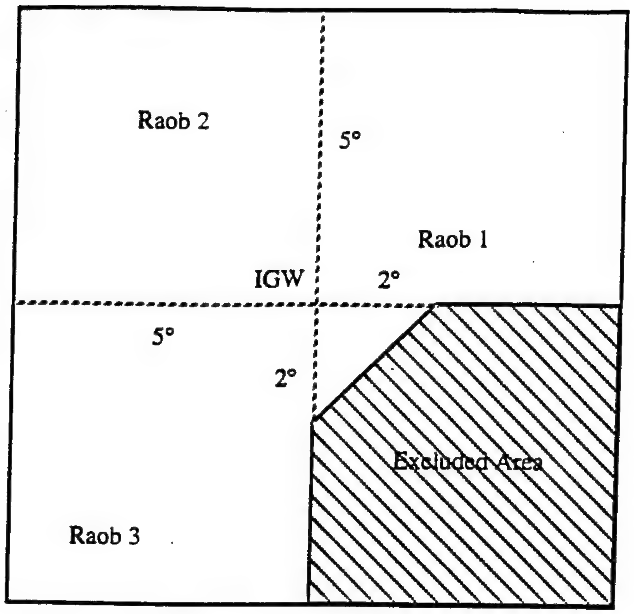

Figure 2. Diagram showing the 10° x 10° area in which the three closest soundings to the IGW are identified.

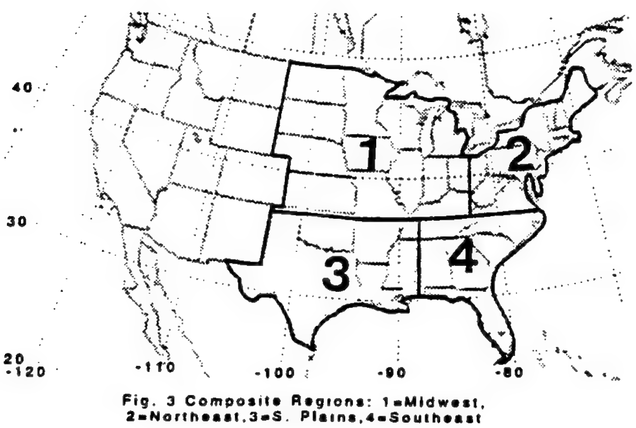

Figure 3. IGW composite regions: 1=Midwest, 2=Northeast, 3=Southern Plains, 4=Southeast.

southwesterly at the top of the inversion, indicative of warm advection. In the layer between the surface inversion and the tropopause, the lapse rate is significantly steeper and in some cases approaches moist neutrality. Winds in this layer increase in magnitude to a maximum at jet level of 35–50 m s^{-1} with little directional shear.

The summer and fall composites (not shown) generally have a similar wind structure (i.e., a low-level veering wind capped by a layer with primarily speed shear). However, the low-level temperature inversion is either shallower (i.e., only up to 900 hPa) or absent altogether. Some of the summer and fall composite soundings possess positive convective available potential energy (CAPE) values. This observation suggests that perhaps IGWs in the summer and fall identified as distinct by Koppel (1995) may be embedded in a convective environment.

4. DISCUSSION

The overall structure of the winter and spring composites is consistent with the Lindzen and Tung (1976) theoretical model of IGW maintenance. The depth of the low-level inversion is similar to those reported by Ralph et al. (1993) and Ramamurthy et al. (1993). The wind speeds in the upper layer of 35–50 m s^{-1} suggest that all but the fastest propagating waves would have a critical level. Although the unidirectional wind shear observed in the composites is not specified by Lindzen and Tung (1976), a similar shear profile in the upper layer also has been observed by Ralph et al. (1993).

These composite soundings also conform to the synoptic pattern identified by Uccellini and Koch (1987). The southwesterly winds in the upper troposphere, together with the relatively high tropopause (see Fig. 4), indicate that IGWs occur in the southwesterly flow downstream (upstream) of a synoptic-scale trough (ridge). The location or movement of jet streaks can not be determined from sounding composites alone. We plan in the near future to composite European Centre for Medium-Range Weather Forecasts (ECMWF) gridded analyses for the 1985–1993 IGW events in order to address this issue and to develop a fully three-dimensional composite picture of the IGW environment.

Another important unresolved issue with forecasting implications is the difference between the composite IGW soundings and composite soundings poleward of a warm front in the absence of IGWs. Clearly, the low-level inversion with veering winds is common to both. Short-term forecasting of IGWs will depend crucially upon the ability to differentiate between an IGW environment and a "typical" warm front. Therefore, we need to identify what, if any, are these differences. Furthermore, if differences exist, are they significant? If not, what factors make the IGW environment unique? In order to address these questions, we also will be developing a composite sounding for "typical" warm fronts in the near future.

Acknowledgments. This research has been supported by the United States Air Force Office of Scientific Research through Grants F49620931 0002 and F496209510492.

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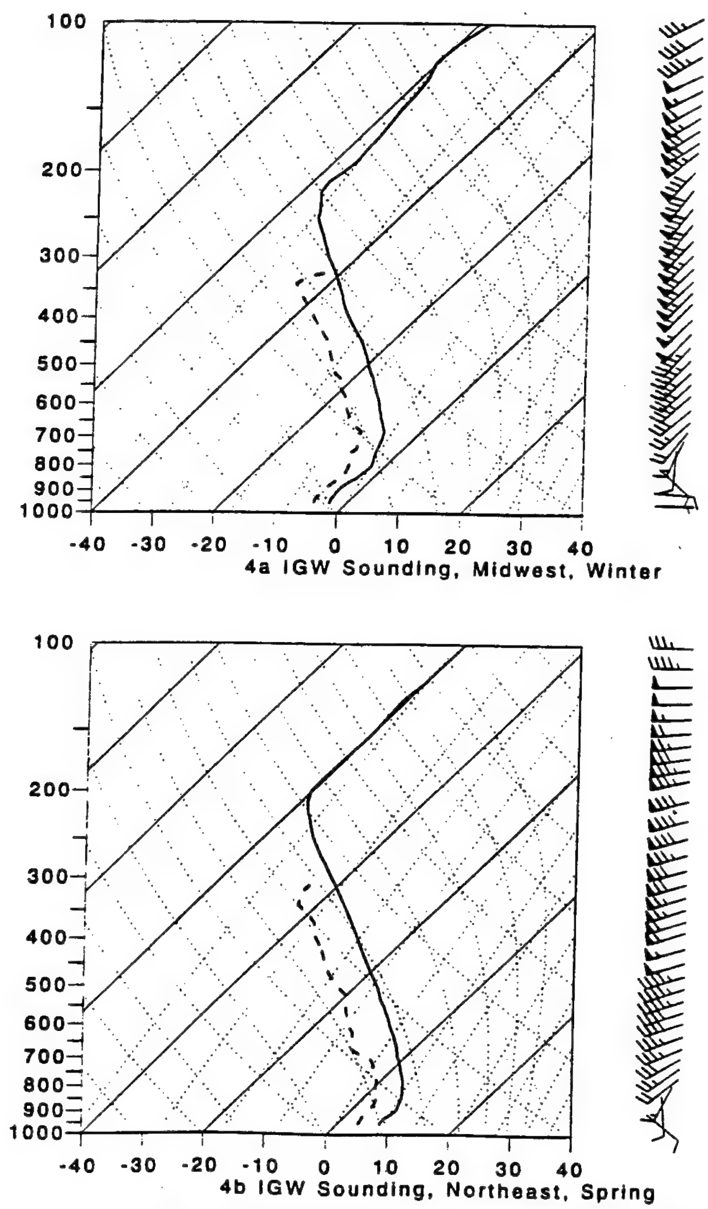

Figure 4. Skew-T Log-P diagram of IGW composite soundings. Temperature (°C, solid), dewpoint (°C, dashed), wind barbs (kts): (a) winter Midwest; (b) spring Northeast.

P21.4

LARGE-AMPLITUDE INERTIA-GRAVITY WAVE ENVIRONMENTS: VERTICAL STRUCTURE AND EVOLUTION

Eric G. Hoffman*, Lance F. Bosart and Daniel Keyser

University at Albany
State University of New York
Albany, New York, USA

1. INTRODUCTION

Observational studies of inertia-gravity waves (IGWs) have focused on identifying and describing the wave itself (e.g. Bosart and Seimon (1988), Koch and Golus (1988), Schneider (1990)). However, recent investigations have begun to illuminate the synoptic environment in which IGWs exist. Uccellini and Koch (1987) showed that for a small sample (13) of published case studies, IGWs occur primarily poleward of a surface frontal boundary beneath the inflection point between an upstream trough and downstream ridge. Uccellini and Koch (1987) also observe a jet streak propagating through the trough into the downstream ridge and suggest that geostrophic adjustment may be an important IGW initiation mechanism. A more extensive climatology of large-amplitude (hourly surface pressure changes > 4.5 hPa) IGW events has recently been compiled by Koppel (1995). This climatology identifies the spatial, seasonal and diurnal distribution of IGWs in the United States

In general, the vertical structure and evolution of the IGW environment has proved difficult to document due to inadequate resolution of the observed data. However, the vertical structure of individual IGW events has been described in detail, utilizing special ancillary observations, by Ralph et al. (1993) and Ramamurthy et al. (1993). Both find low-level inversions capable of acting as wave ducts superposed by a near neutral layer containing a wave critical level. These vertical structures match well with the theoretical model proposed by Lindzen and Tung (1976) for IGW maintenance. While these and other studies of IGW events have examined the existence of a wave duct and wave critical layers, the characteristic vertical structure of the IGW environment and its evolution has yet to be fully elucidated.

The goal of this research is to identify the evolution and characteristic vertical structures of environments conducive to the formation and presence of large-amplitude IGWs. The vertical structure of IGW environments is examined by constructing regional and seasonal composites of soundings nearest to IGW occurrences identified by Koppel (1995). Since our research is tied closely to Koppel (1995), a brief review of her methodology and results is presented in section 2. Section 3 will describe the data and the objective sounding composite methodology. A discussion of these results is presented in section 4.

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2. IGW CLIMATOLOGY

Koppel (1995) identified large-amplitude IGW occurrences (hereafter, IGW will refer to large-amplitude IGW) in the United States through subjective examination of hourly station pressure changes greater than 4.5 hPa from a network of 150-200 National Weather Service observing stations. The hourly surface reports were available from archives at the National Center for Atmospheric Research (NCAR) for two periods: 1949-1963 and 1984-1993. She further subjectively categorized the IGW occurrences into those in which the IGW signature was embedded within other meteorological events (i.e., convection or cyclone passage) and distinct IGWs. Koppel (1995) then compiled the regional (see Fig. 1), seasonal, and diurnal distribution and frequency of IGWs.

Her primary results indicate that IGWs occur almost exclusively east of the Rocky Mountains (see Fig. 1). Maximum IGW frequency occurs in a primarily north-south axis extending from the Upper Midwest into Arkansas and Oklahoma. Secondary axes extend eastward from the primary axis across the Great Lakes and the Southeast. The monthly frequency distribution (not shown) indicates a maximum in the late winter/early spring (Feb., Mar., Apr.) and a minimum in late summer/early fall (Aug., Sep., Oct.). The diurnal distribution (not shown) shows two peaks: near 0300 LST with a second higher maximum near 1200 LST. Koppel (1995) also showed composite 500 hPa and surface structure for IGW events that correspond closely to the synoptic signatures outlined by Uccellini and Koch (1987).

3. IGW SOUNDING COMPOSITES

3.1 Data and Methodology

Construction of regional and seasonal composite soundings associated with IGWs is accomplished using Koppel's (1995) results and the North American sounding data (1946-1992) archived on compact disc (CD). An objective methodology has been used to identify the individual soundings of the composite. Our composite is restricted to soundings corresponding only to those IGW events that Koppel (1995) categorized as distinct (see above). The three closest sounding stations in time and space to each IGW occurrence are identified excluding those soundings stations located far to the southeast of the IGW (see Fig. 2). Exclusion of soundings in this sector is based on results from Uccellini and Koch (1987) and Koppel (1995) indicating that IGWs occur primarily poleward of warm fronts. Soundings in the excluded area are more likely to be located in the warm sector of a cyclone, equatorward of the warm front. We search the sounding CD data and include the closest sounding of the three for which data are available. Individual soundings corresponding to more than one of the IGW occurrences are only added to the

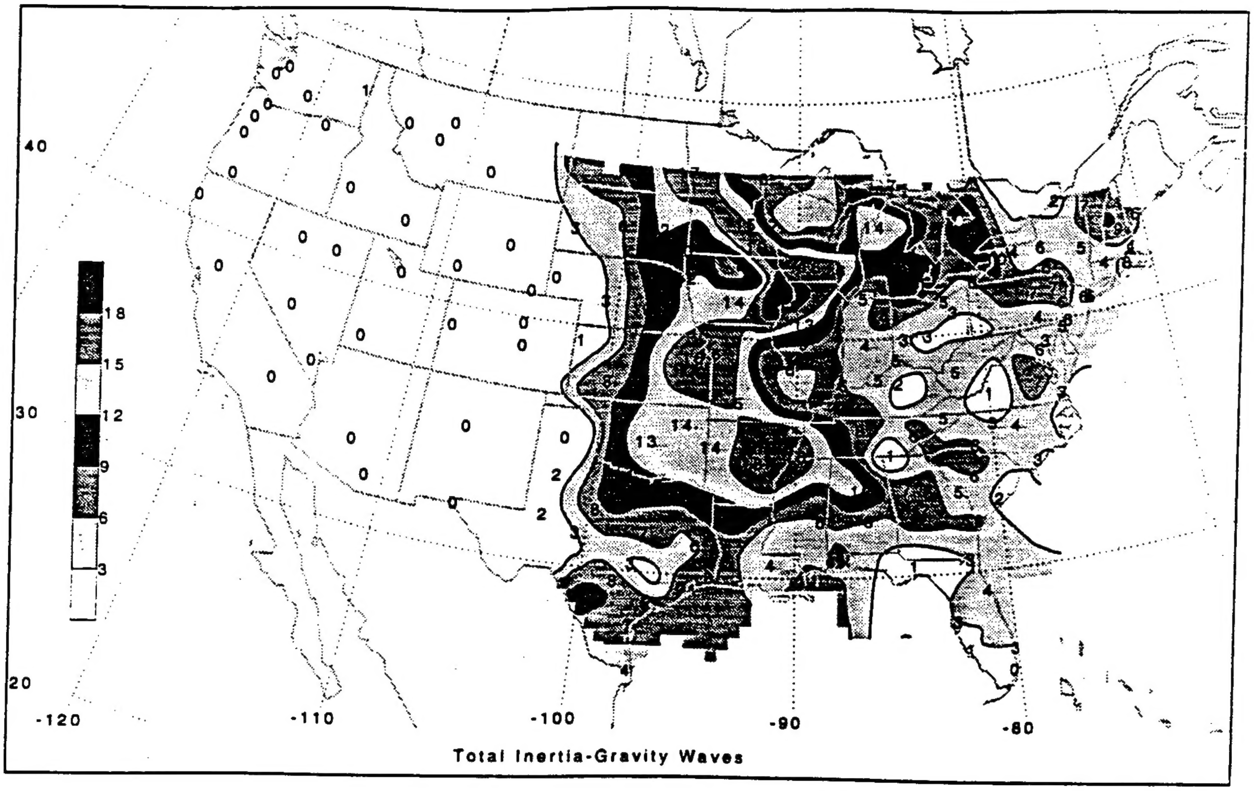

Figure 1. 25 Year (1949-1963 and 1984-1993) Inertia-Gravity Wave Climatology (After Koppel, 1995).

composite once. After the appropriate sounding has been identified, the temperature, dewpoint temperature, height, and u and v wind components are linearly interpolated with respect to the log of pressure to 10 hPa increments from 1000 to 100 hPa. Finally, because climatological temperatures in the troposphere vary seasonally and meridionally, each sounding is identified with one of four regions (see Fig. 3): 1) Midwest, 2) Northeast, 3) Southern Plains and 4) Southeast. Each variable is composited by region and season at the interpolated levels.

3.2 *Results*

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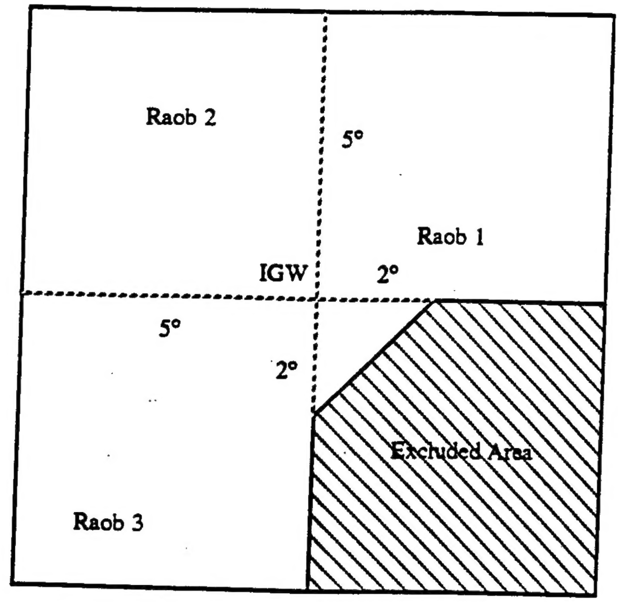

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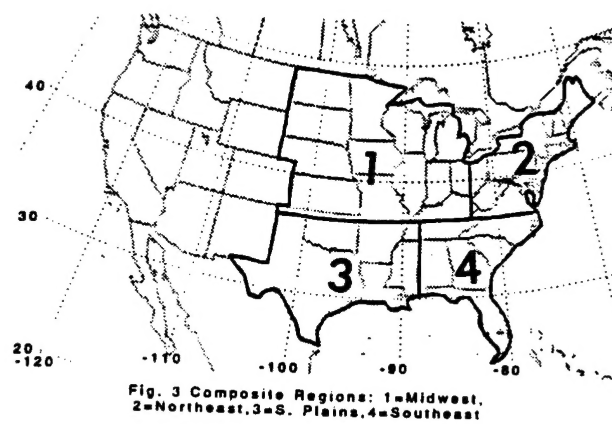

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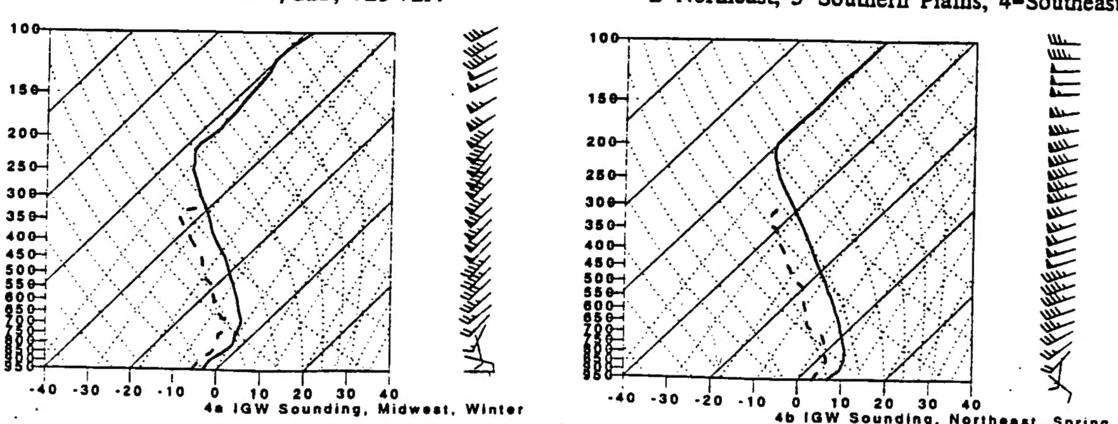

Figure 4. Skew-T Log-P Diagram of IGW Composite Soundings. Temperature (°C, solid), Dewpoint Temperature (°C, dashed), Wind barbs (kts): a) Midwest (winter); b) Northeast (spring).

AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT) REPORTING FORM

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT Program. By accepting this Grant which bestows the AASERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information requested below. This information should be provided to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R&T and Grant numbers found on Page 1 of Grant)

a. University at Albany/SUNY
University Name

b. F496209310002 (A)
Grant Number

c. F496209510492 (B)
R&T Number

d. Lance F. Bosart
P.I. Name

e. From: 1 September 95 To: 31 August 1996
AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement".

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a. Funding: $ 309,423

b. Number FTEGS: 2

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period.

a. Funding: $ 309,423

b. Number FTEGS: 1

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

a. Funding: $ 117,061

b. Number FTEGS: 1

c. Number UGS: 0

VERIFICATION STATEMENT: I hereby verify that all students supported by the AASERT award are U.S. citizens.

Lance F. Bosart
Principal Investigator

11 December 1996
Date